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Compacted Chalk Putty-Cement Blends: Mechanical Properties and Performance

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ABSTRACT: Compaction and Portland cement addition are amongst promising ground improvement procedures to enhance the mechanical properties of chalk putty. Present investigation intends to compute the impact of Portland cement content and dry density on the mechanical properties (stiffness and strength) and performance (durability) of compacted chalk putty-cement mixes. The most significant addition to knowledge is quantifying the accumulated loss of mass (ALM) after wet/dry cycles, initial shear modulus (G_0) and unconfined compressive strength (q_u) as a function of the porosity/cement index. In addition, it is empirically revealed the existence of an exclusive relation connecting accumulated loss of mass divided by the number of wetting/drying cycles and porosity/cement index. Besides, a power relation was found between initial shear modulus at small strains after wet-dry cycles (G_0) and average loss of mass after each cycle. This broadens the applicability of such index by demonstrating it controls not only strength and stiffness but also endurance performance of compacted chalk putty-Portland cement blends.

Keywords: Chalk putty, Portland cement, durability, shear modulus, strength, porosity/cement index.

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INTRODUCTION

Chalk is a soft, fine-grained, easily pulverized white-to-grayish porous sedimentary rock whose chemical composition is basically calcium carbonate. This material is a pure limestone and its calcium carbonate content can exceed 98% (Clayton and Matthews 1987; Bell et al 1999; Bloomfield et al 1995).

Chalk deposits occur in Western Europe, extending from northern Germany and Denmark, to eastern and southeastern England, Ireland and Scotland. It covers about 15% of England's surface area (Bundy 2013), notably in the cliffs of Dover along the English Channel. Part of the North Sea is floored by chalk as well. The material may also be found in central and southern Europe, eastwards from Poland to the northern slopes of the Caucasus and to the Black Sea, Iraq, the Caspian Sea and south western Siberia (Bell et al 1999).

According to Bundy (2013) and Bell et al (1999), this material was formed in Cretaceous seas, around 100 to 60 million years ago and 200 to 300 meters deep, due to a marine incursion over Southern England and beyond. These deposits of marine origin were formed under gravity while coccolith debris descended to the seabed. This is the reason why chalk is a highly porous and a granular material whose strength is given by the interlocking of grains. The seafloor compaction and cementation was able to provide enough strength for the material to bear later overburden without collapsing. Then, the intact strength of the chalk comes from three components: cementation, inter-granular friction and inter-granular molecular bonding.

However, a transition from intact chalk to slurry (called 'putty') takes place in any environment where energy, which may be a result of shearing, vibration, crushing or degradation of the cementation, breaks down the cement bonds. The original material breaks down into finer grains and the cementation resistance is lost. Some putties are a result of natural processes, although many of them are caused by the manipulation of the intact chalk during civil engineering projects (Bundy 2013).

Chalk is an abundant material and it is one of the main sources of earthworks material in the UK (Lord et al 2002). It has been successfully used in the construction of embankments for railways, trunk roads and motorways, particularly in the south of England. Nevertheless, there continue to be problems during the earthworks processes related to the generation of putty chalk from mechanical handling and crushing of the material. As such, there has been considerable effort in developing specifications engineered chalk fills to avoid construction problems and obtain satisfactory embankment structures from the first symposium Chalk in Earthworks and Foundations in 1965 (Lord et al 2002).

It is believed that one of the ways of improving chalk behavior is with the addition of Portland cement or lime. Since the construction of the Eurotunnel, millions of tons of soil have been treated with quicklime for the construction of highways, for the high-speed train (TGV) in the north of France and more recently for a TGV in the region of Champagne. In all situations, the main objective has always been the rapid and permanent increase of the load capacity for the construction of embankments (Hornych 2004). In these cases, however, the predominant reaction was the carbonation of the quicklime, not the pozzolanic reactions.

The use of artificially cemented materials (using Portland cement and lime) usually results from the application of physical-chemical stabilization, which occurs with the addition of the cementing agent, and mechanical stabilization through compaction. The objective is to improve the mechanical properties related to the resistance, deformability, permeability and durability of the soil for the use in the solution of several geotechnical problems. These materials have a great deal of application in the execution of bases of pavements, in containment of masses, in the execution of shallow foundations and in the prevention of liquefaction in sands.

There is no dosage formulation indicating the mechanical behavior of compressive strength, durability, and stiffness of compacted chalk-cement mixtures yet. This study focuses on the effect of cement mixed with chalk putties on some of main properties of road materials, such as unconfined compression strength, initial stiffness (G_0) and durability. It aims to examine the behavior of chalk putty to assess its potential use as a sub-base material for low volume roads when combined with Portland cement and compaction.

A logical dosage procedure for soil-Portland cement was created by Consoli et al (2007) taking into consideration the porosity/cement index (η/C_{iv}) as a proper parameter to assess unconfined compression strength (q_u) of soil-Portland cement mixes. No previous research has examined the applicability of the porosity/cement index (η/C_{iv}) for compacted chalk putty-cement blends in terms of loss of mass after dry/wet cycles to check durability, strength (q_u) and shear modulus at small strains (G_0). This study targets to determine straight relations between η/C_{iv} and q_u, G_0 and accumulated loss of mass (ALM) after wetting and drying cycles (durability) for compacted chalk putty-cement blends.

BACKGROUND

Studies by Consoli et al (2007) led to the conclusion that the ratio between porosity of a soil-cement blend and its volumetric cement content (η/C_{iv}) might be an interesting index to interpret unconfined compression strength (q_u) results, considering the influence of both volume of voids and volume of cement of considered specimens. It can be interpreted that for a given variation in the porosity (η), a proportional change in the volumetric cement content (C_{iv}) would balance the loss of the resistance. Consoli et al (2017) has shown that such proportionality is effective in clean granular soils treated with Portland cement. However, the presence of fines (silt plus clay size particles) in soils treated with Portland cement requests an adjustment in the volumetric cement content (C_{iv}) by an exponent (generally equal to 0.28 in the case of soil containing fines-cement). This adjustment is a tool to make the rate of change of resistance due to η and the rate of change of resistance of the inverse of C_{iv} follow the same ratio, as shown experimentally by Consoli et al (2016) and theoretically by Diambra et al (2017). The q_u - η/C_{iv} relation is extremely useful for dosage and control of soil-cement mixtures in the field. This technique allows the choice of a quantity of cement and compaction energy that provides a blend that meets the design strength (Consoli et al 2016, 2017).

The initial stiffness (G_0) might also be an important information for the geotechnical engineer, since it might be used as a control tool or as a reference parameter that is correlated with other properties in Geomechanics. The stiffness of the cemented soil increases with increasing amount of cement (Clough et al 1981, Leroueil and Vaughan 1990, Hight and Jardine 1993, Cuccovillo and Coop 1997 and Vaughan 1997). In addition to it, Chang and Woods (1992) have shown that the increase of the shear modulus at small strains in sands also depends on the number of points of contact between the particles. According to Consoli et al (2012), the porosity/cement index is shown to be an appropriate parameter for evaluating both stiffness and strength of soil-cement mixtures.

Durability is related to the ability of a material to keep its structural integrity under the conditions to which it is exposed (Dempsey and Thompson 1968). The main factors that affect the structural integrity of a stabilized material are the variations of humidity and temperature and the repeated loads. Durability may be the most significant property of the behavior of materials stabilized with cement, being influenced by the particle size distribution of the aggregate, cement content, curing time and saturation. For this reason, studies have been carried out to evaluate durability of soil-cement mixtures, most of them centered on two

ASTM standards: wetting and drying (ASTM D559 2015) and freezing and thawing (ASTM D560 2013). The purpose of the durability tests is the simulation of field environmental conditions in the sample. ASTM D559 (2015) specifies the durability test in which it is measured as a function of the percentage of mass loss during 12 cycles of wetting, drying and brushing of the samples. The Portland Cement Association (1956) establishes the maximum loss of mass allowed in projects of pavements depending on the type of soil. Shihata and Baghdadi (2001) immersed groups of silty sand-cement specimens in saline water for different periods prior to running 12 wetting-drying cycles followed by brushing strokes. The authors found that soils with larger amounts of fines presented higher weight loss values in such tests. They also observed a close relationship between percent mass loss and reduction of unconfined compressive strength after the cycles. Guthrie et al (2008) reported that brushing is sometimes omitted due to the variability associated with the process, being replaced by the simple compressive strength test after 12 wetting-drying cycles. Zhang and Tao (2008) performed durability tests in low plastic silty clay stabilized with cement. The authors observed that the mass loss decreased with the increase in cement contents, but increased with the increase of water-cement ratio. Theivakularatnam and Gnanendran (2015) observed that the accelerated reaction of binders due to increasing temperature masked the detrimental effect of the wet-dry cycles. Horpibulsuk et al (2016) studied the durability against wetting–drying cycles of water treatment sludge–fly ash geopolymer and silty clay–cement systems. Compared with a traditional clay–cement sample at the same initial soaked strength, the water treatment sludge–fly ash geopolymer sample exhibits higher durability. Avirneni et al (2016) assessed the durability of reclaimed asphalt pavements (RAP) mixed with fly ash and sodium hydroxide (NaOH). It was observed that for high RAP and low NaOH contents (for the same fly ash amounts) the weight loss is high.

EXPERIMENTAL PROGRAM

The materials and methods used in present research are discussed below.

Materials

The chalk used in the testing was collected from a disused chalk pit located in St Nicholas at Wade, Kent (UK). The site was recently used for pile and cone penetration test research activities (Diambra et al. 2014; Ciavaglia et al. 2017a; Ciavaglia et al. 2017b) and the in-situ chalk was characterized as CIRIA Grade A/B (Lord et al. 2002) low to medium density. Lumps of intact chalk collected from the site have been oven dried and crushed in the laboratory to sandy silt (ML) (ASTM D2487, 2006), which turns into chalk putty when mixed with water. The characteristics and Atterberg limits of the crushed chalk are summarized in Table 1.

High early strength (Type III) Portland cement (ASTM C150 2016) was used through this investigation. Its rapid increase of resistance permitted selecting seven days as the curing period. Cement grains specific gravity is 3.15.

Distilled water was employed both for characterization tests and molding specimens for the mechanical tests.

Methods

Molding and Curing of Specimens

For strength (unconfined compression) and stiffness (ultrasonic pulse velocity) tests, cylindrical specimens of 50 mm diameter and 100 mm height were employed. For durability (wetting and drying) tests, cylindrical specimens of 100 mm diameter and 120 mm height were utilized. An aimed dry density for a particular specimen was then established as a result of the dry compacted chalk putty-Portland cement mix divided by the total volume of the specimen. As shown in Eq. (1) (Consoli et al 2016), porosity (η) is a function of the dry density (γ_d) and Portland cement content (C), defined as the ratio between weight of cement and weight of dry soil. Each substance (chalk putty and Portland cement) has a unit weight of solids (γs_{CP} and γs_C), which also requires to be accounted for computing porosity.

$$\eta = 100 - 100\left\{\left[\frac{\gamma_d}{1+\frac{C}{100}}\right]\left[\frac{1}{\gamma s_{CP}} + \frac{\frac{C}{100}}{\gamma s_C}\right]\right\} \tag{1}$$

Once the chalk putty and Portland cement were weighed, they were blended until the mix attained uniformity. Moisture content of 27% (optimum for standard effort) for the chalk putty-Portland cement blends was then supplemented, continuing the mix process until a homogeneous paste was obtained. Specimens were statically compacted in 3 layers inside a cylindrical mold. Subsequently to molding, specimens were removed from the molds and their weights, diameters and heights were measured with precisions of nearly 0.01 g and 0.1 mm, respectively. The specimens were cured in a humid room at 23º ± 2ºC and relative moisture of about 95%. Maximum dry unit weight for standard Proctor compaction effort was found to be 15.3 kN/m^3.

Unconfined Compression Tests

Compression tests followed standard ASTM C39 (2010). Before testing, specimens were immersed under water for 24 h to eliminate suction (Consoli et al 2011). Specimens were molded with 27% of moisture content (optimum moisture content for standard Proctor compaction effort), dry unit weights of 15.3 kN/m^3 (maximum dry unit weight for standard Proctor compaction effort), 14.3 kN/m^3 and 13.3 kN/m^3, Portland cement contents of 3%, 5% and 7% [values chosen according to international (Mitchell 1981) and Brazilian (Consoli et al. 2007, 2016) experiences] and cured for 7 days.

Ultrasonic Pulse Velocity Tests and Elastic Parameters

Elastic parameters of artificially cemented chalk putty at tiny deformations may be acquired carrying out ultrasonic pulse velocity tests following standard ASTM D2845 (2008). Transducers are attached to the top and bottom of the specimens using a coupler gel. Specimens were molded at three different dry densities (13.3 kN/m^3, 14.3 kN/m^3 and 15.3 kN/m^3), using three distinct early strength Portland cement contents (3%, 5% and 7%) and a unique moisture content of about 27%. They were cured for 7 days before testing.

Durability Tests

Durability (wetting-drying cycles) tests of compacted chalk putty-Portland cement mixtures were completed according to standard ASTM D559 (2015). Test procedures determine mass losses produced by 12 wetting-drying series starting after 7 days of curing time. Every cycle begins by oven drying for 42 h at 71º ± 2ºC. Specimens are then brushed a number of times using a force of approximately 13.3 N. Finally, specimens are immersed under water for 5 h at 23° ± 2°C. Specimens were molded with three different dry densities (13.3 kN/m^3, 14.3 kN/m^3 and 15.3 kN/m^3), using three distinct early strength Portland cement contents (3%, 5% and 7%) and a moisture content of 27%. They were cured for 7 days before testing.

RESULTS AND DISCUSSION

Influence of the Porosity/Cement Index on q_u

Figure 1 reports the results of the unconfined compression tests by showing q_u as a function of an adjusted porosity/cement index $\eta/(C_{iv})^{0.28}$ [defined as porosity (η) divided by the volumetric cement content (C_{iv}), the latter expressed as a percentage of cement volume to the total volume of the chalk putty-Portland cement mixes (Consoli et al 2007, 2016)] for the curing period studied (7 days).

The capability of the adjusted porosity/cement index to normalize strength of cement treated fine-grained soils has been shown by Consoli et al (2016). These authors obtained a unique form of correlation between q_u and η/C_{iv} for several fine-grained soils mixed with Portland cement using the adjustment coefficient of 0.28 in C_{iv}. Even with the variation of moisture contents, porosities, cement amounts and curing periods, it was possible to establish and validate a unique relationship that determines the resistance of fine-grained soils with different characteristics (particle size distribution, plasticity index), moisture content and curing periods up to 28 days. The adjustment coefficient 0.28 was also used in present study. Figure 1 indicates that the adjusted porosity/cement index is helpful in normalizing strength results for chalk putty-Portland cement mixtures, leading to a very good correlation (R^2 = 0.98) between $\eta/(C_{iv})^{0.28}$ and q_u.

$$q_u\,(kPa) = 1.37x10^9 \left[\frac{\eta}{C_{iv}^{\ 0.28}} \right]^{-3.87} \qquad (2)$$

It was observed that q_u increased with the increase of the cement content and compaction of the specimens. The values of q_u obtained varied from 349.2 kPa (3% of cement content and 13.3 kN/m³) to 1602.0 kPa (7% of cement content and 15.3 kN/m³), showing how effective were the amount of cement and the compaction in the specimens. According to Consoli et al (2007), the gain of resistance with reduction of porosity is caused by the most effective cementation due to the higher number of contacts among the existing particles. In addition, there is a better distribution of stress inside the specimen and a higher capability of the material to mobilize friction at lower porosities, which contributes to the increase of the resistance. Therefore, Figure 1 shows the influence of the level of cementation and the level of compaction on the strength of the mixtures. It has been shown that the reduction of porosity (η) and the increase in the volumetric cement content (C_{iv}) led to the increase of unconfined compression strength (q_u).

The q_u - $\eta/(C_{iv})^{0.28}$ relation established for the studied chalk putty-Portland cement mixes can be used to estimate any specific design strength.

Influence of the Porosity/Cement Index on G_0

A similar analysis has been also performed for the results of the ultrasonic pulse velocity tests, which enabled to evaluate the initial shear stiffness (G_0) of the tested specimens (Figure 2). Results show that $\eta/(C_{iv})^{0.28}$ also controls G_0 for compacted chalk putty-Portland cement mixes. A sound correlation ($R^2 = 0.94$) is detected concerning $\eta/(C_{iv})^{0.28}$ and G_0 of the compacted chalk putty-Portland cement mixtures considered, reflecting 7 days of curing [Eq. (3)].

$$G_0(MPa) = 2.4x10^6 \left[\frac{\eta}{C_{iv}^{0.28}}\right]^{-2.07} \tag{3}$$

As in the case of strength, the initial stiffness also increases with the increase of cement content and compaction of the specimens. The higher the compaction, the smaller the wave arrival time, since the sound wave (ultrasound) propagates more rapidly in solid than in air, thus increasing the measured stiffness. The values obtained varied from 704.9 MPa (considering 3% of cement content and 13.3 kN/m³) to 1546.3 MPa (reflecting 7% of cement content and 15.3 kN/m³).

Influence of the Cement Content, Porosity and Porosity/Cement Index on Durability (wetting and drying cycles) of Compacted Chalk Putty-Cement Blends

The loss of mass and stiffness changes of the chalk putty-Portland cement mixtures after each of the 12 wet-dry cycles, followed by brushing, were analyzed. Initially, the individual mass loss in each cycle was plotted. The middling loss of mass (MLM) is the average loss of mass of each tested specimen. It is obtained adding up the loss of mass during all cycles and dividing by the number of cycles, which is illustrated by the dashed lines in Figure 3. It was observed that the higher the compaction and cement content of the specimen, the lower the loss of mass, since the specimen becomes less porous, and the cement increases the bonds among the grains, making it difficult to pull out material during brushing. The middling loss of mass during the cycles ranged from 2.35% (for the specimen of lower dry unit weight and lower cement content) to 0.5% (for the specimens with higher dry unit weight and higher cement content).

In order to visualize the total loss of mass during the cycles, the accumulated loss of mass (ALM) was calculated in each cycle, and the values were plotted in Figure 4. The ALM was calculated by adding the loss of mass of previous cycles in the current cycle. It was observed that the accumulated loss of mass (ALM) during the cycles allowed adjusting a straight line for each specimen, with a steeper slope for the specimen of 3% cement content and 13.3 kN/m³ and a less accentuated slope for the specimen of higher percentage of cement content (7%) and 15.3 kN/m³.

The ALM reached almost 30% at the end of 12 cycles in the specimen of 13.3 kN/m³ and 3% of cement content, being roughly 5% in the specimen molded with 7% of cement content and 15.3 kN/m³ of dry unit weight. These data showed how much this increase in cement content and specimen compaction is significant in increasing the durability of the mixture.

In order to observe the behavior of the specimens as a function of the porosity/cement index (η/C_{iv}), the ALM after 3, 6, 9 and 12 cycles was plotted as a function of η/C_{iv} adjusted with the coefficient 0.28. Figure 5 shows compacted chalk putty-Portland cement blends accumulated loss of mass (ALM) versus adjusted porosity/cement index [$\eta/(C_{iv})^{0.28}$] after 3 [Eq. (4) – R^2 = 0.98], 6 [Eq. (5) – R^2 = 0.97], 9 [Eq. (6) – R^2 = 0.94] and 12 [Eq. (7) – R^2 = 0.95] wetting and drying and brushing cycles.

$$ALM(\%) = 4.45x10^{-8}\left[\frac{\eta}{C_{iv}^{0.28}}\right]^{3.70} \quad (4)$$

$$ALM(\%) = 2.69x10^{-8}\left[\frac{\eta}{C_{iv}^{0.28}}\right]^{3.95} \quad (5)$$

$$ALM(\%) = 7.40x10^{-8}\left[\frac{\eta}{C_{iv}^{0.28}}\right]^{3.77} \quad (6)$$

$$ALM(\%) = 5.37x10^{-8}\left[\frac{\eta}{C_{iv}^{0.28}}\right]^{3.92} \quad (7)$$

Finally, by dividing the accumulated loss of mass of each specimen by the number of cycles, a single curve of loss of mass (considering 3, 6, 9 and 12 cycles) by the number of cycles (ALM/NC) was adjusted as a function of $\eta/(C_{iv})^{0.28}$ (see Figure 6), providing a coefficient of determination (R^2) of 0.89 [see Eq. (8)].

$$\frac{ALM}{NC}(\%) = 7.03x10^{-9}\left[\frac{\eta}{C_{iv}^{0.28}}\right]^{3.84} \quad (8)$$

It is possible to observe, for the first time ever, that the porosity/cement index also controls the durability of compacted chalk putty-Portland cement blends. Thus, the porosity/cement index controls strength, stiffness and endurance of the compacted chalk putty-Portland cement blends.

After brushing specimens after each cycle, initial stiffness (G_0) measurements were performed for cycles 3, 6, 9 and 12 to evaluate how G_0 was altered during the durability test. It was observed that the stiffness ranged from approximately 1,000 MPa to 2,250 MPa and the initial stiffness increased the higher the cement content and dry unit weight of the specimens. It was observed that the G_0 values measured after 3, 6, 9 and 12 cycles were approximately constant for each imposed combination of material porosity and cement content (see Figure 7). However, the comparison with the values reported in Figure 3 demonstrates that these values are systematically higher than those measured before the application of wetting-drying cycles. Such behavior can be attributed to the fact that the pozzolanic reactions in the specimens were accelerated by oven drying at 71°C and after 3 cycles (approximately 14 days of cure) there are no more significant reactions in the specimens after that. In spite of the specimens being submitted to wetting, drying and brushing cycles, it did not affect the propagation time of the ultrasound wave inside the specimen, not affecting the initial stiffness of the soil mass.

In order to verify the stiffness behavior as a function of the loss of mass, the initial stiffness versus the middling loss of mass (MLM) was plotted after 3, 6, 9 and 12 cycles for each specimen (see Figure 8). A power trend line was adjusted to the results ($R^2 = 0.94$):

$$G_0(MPa) = 159.9[MLM]^{-0.48} \tag{9}$$

It was obtained for the compacted chalk putty-Portland cement blends a unique relation between G_0 and MLM. This relationship suggests that further studies, considering distinct soils and binders, should be carried out in order to define possible trends that might be used to determine durability through G_0 measurements instead of loss of mass (the latter considerably time consuming and whose results might vary regarding the skills of the operator).

CONCLUSIONS

It was observed that the addition of high early strength Portland cement and the increase in dry unit weights produced a significant improvement of the mechanical properties of compacted chalk putty-Portland cement blends.

The presented experimental results show how the increase of a small amount of cement (from 3 to 7%) and of compaction (γ_d ranging from 13.3 to 15.3 kN/m^3) may result in an increase in the unconfined compression strength of approximately 4 times and an increase in the initial stiffness of approximately 2 times. The proposed relationship for strength and stiffness (Eqs. 2 and 3) can be used in projects involving the studied chalk stabilized with Portland cement, providing the correct dosage of soil-cement to be adopted for achieving the required design strength and stiffness.

The accumulated loss of mass values divided by the number of cycles is also a function of the η/C_{iv} adjusted for the coefficient 0.28 and this relationship provides a dosage for the blends depending on the design stiffness specifications. No variation of the initial stiffness from cycle 3 to 12 is observed. It is concluded that the reactions are accelerated by oven drying at 71°C and, after 3 cycles, there are no more significant reactions in the specimens.

The loss of mass is an important parameter in the design of pavements stabilized with cement, since some limits must be respected. The Portland Cement Association (1956), for example, establishes 10% of accumulated loss of mass as a limit for A-2-6 type soils, to which the crushed chalk studied in present research corresponds. From the specimens tested, only the ones containing 7% of cement content provided a dosage that fulfills the requirements of this standard for the execution of paving projects.

This work provides a basis for how cement chalk blends behave in terms of strength, durability and initial stiffness, assessing behavior trends and showing how chalk putties can be improved with cement for the application in paving and soil stabilization projects.

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REFERENCES

ASTM (2006). “Standard classification of soils for engineering purposes.” *ASTM D2487*, West Conshohocken, Philadelphia.

ASTM (2008). “Standard test method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock.” *ASTM D2845*, West Conshohocken, Philadelphia.

ASTM (2010). “Standard test method for compressive strength of cylindrical concrete specimens.” *ASTM C39*, West Conshohocken, Philadelphia.

ASTM (2013). “Standard test methods for freezing and thawing compacted soil-cement mixtures.” *ASTM D560*, West Conshohocken, Philadelphia.

ASTM (2015). “Standard test methods for wetting and drying compacted soil-cement mixtures.” *ASTM D559*, West Conshohocken, Philadelphia.

ASTM (2016). “Standard specification for Portland cement.” *ASTM C150*, West Conshohocken, Philadelphia.

Avirneni, D.; Peddinti, P.R.T.; Saride, S. (2016). "Durability and long term performance of geopolymer stabilized reclaimed asphalt pavement base courses." *Construction and Building Materials*, 121, 198-209.

Bell, F.G.; Culshaw, M.G.; Cripps, J.C. (1999). “A review of selected engineering geological characteristics of English chalk.” *Engineering Geoscience*, 2, 355-368.

Bloomfield, J.P.; Brewerton, L.J.; Allen, D.J. (1995). “Regional trends in matrix porosity and dry density of the Chalk of England.” *Quarterly Journal of Engineering Geology*, *28*, 131-142.

Bundy, S.P.S. (2013). "Geotechnical properties of chalk putties." *PhD thesis*, University of Portsmouth, UK.

Chang, T.; Woods, R.D. (1992). "Effect of particle contact bond on shear modulus." *Journal of the Geotechnical Engineering,* New York, 118(8), 1216-1233.

Ciavaglia, F.; Carey, J.; Diambra, A. (2017a). "Time-dependent uplift capacity of driven piles in low to medium density chalk." *Géotechnique Letters* (DOI: 10.1680/jgele.16.00162).

Ciavaglia, F.; Carey, J.; Diambra, A. (2017b). "Monotonic and cyclic lateral tests on driven piles in Chalk". *Proceedings of the Institution of Civil Engineers-Geotechnical Engineerin*g, 1-14.

Clayton, C.R.I.; Matthews, M.C. (1987). "Deformation, diagenesis and mechanical behaviour of chalk." In: ME Jones and RMF Preston (Eds.) Deformation of Sediments and Sedimentary Rocks. *Geology Society Special Publication* 29, p. 55-62.

Clough, W.; Sitar, N.; Bachus, R.C.; Rad, N.S. (1981). "Cemented sands under static loading." *Journal of Geotechnical Engineering Division*, New York, v.107, n.6, p.799-817.

Consoli, N.C.; Foppa, D.; Festugato, L.; Heineck, K.S. (2007). "Key parameters for strength control of artificially cemented soils." *Journal of Geotechnical and Geoenvironmental Engineering*, 133(2), 197–205.

Consoli, N.C.; Dalla Rosa, A.; Saldanha, R.B. (2011). "Variables Governing Strength of Compacted Soil–Fly Ash–Lime Mixtures." *Journal of Materials in Civil Engineering,* v. 23(4), 432–440

Consoli, N.C.; da Fonseca, A.V.; Silva, S.R.; Cruz, R.C. and Fonini, A. (2012). "Parameters controlling stiffness and strength of artificially cemented soils". *Géotechnique*, 62(2), 177-183.

Consoli, N.C.; Ferreira, P.M.V.; Tang, C.S.; Marques, S.F.V.; Festugato, L.; Corte, M.B. (2016). "A unique relationship determining strength of silty/clayey soils – Portland cement mixes." *Soils and Foundations,* 56(6), 1082-1088.

Consoli, N.C.; Marques, S.F.V.; Floss, M.F.; Festugato, L. (2017). "Broad-spectrum empirical correlation determining tensile and compressive strength of cement-bonded clean granular soils." *Journal of Materials in Civil Engineering*, 29(6), 06017004.

Cuccovillo, T.; Coop, M.R. (1993). “The influence of bond strength on the mechanics of carbonate soft rocks.” *Proceedings of the 1st International Symposium on Geotechnical Engineering of Hard Soils–Soft Rocks*, Athens, 1, 447-455.

Diambra, A.; Ciavaglia, F.; Harman, A.; Dimelow, C.; Carey, J.; Nash, D.F.T. (2014). “Performance of cyclic cone penetration tests in chalk.” *Géotechnique Letters,* 4(3), 230–237 (DOI:10.1680/geolett.14.00050).

Dempsey, B.J.; Thompson, M.R. (1968). “Durability properties of lime-soil mixtures.” *Highway Research Record 235*, Highway Research Board, Washington, D.C., 61–75.

Guthrie, W.; Roper, M.; Eggett, D. (2008). “Evaluation of laboratory durability tests for stabilized aggregate base materials.” *PCA R&D Serial No. 3045*, p. 17.

Hight, D.W.; Jardine, R.J. (1993). “Small-strain stiffness and strength characteristics of hard London tertiary clays.” In: *Int. Symposium on Geotechnical Engineering of Hard Soils – Soft Rocks*, Athens: 1993. Proceedings… Rotterdam: A. A. Balkema, 1, 533- 552.

Hornych, P.; Hameury, O.; Puiatti, D. (2004). “Laboratory and in situ evaluation of stabilization of limestone aggregates using lime”. *In: Pavements Unbound: Proceedings of the 6th International Symposium on Pavements Unbound* (UNBAR 6), 6-8 July 2004, Nottingham, England. CRC Press, 2014. p. 291.

Horpibulsuk, S.; Suksiripattanapong, C.; Samingthong, W.; Rachan, R.; Arulrajah, A. (2015). “Durability against wetting–drying cycles of water treatment sludge–fly ash geopolymer and water treatment sludge–cement and silty clay–cement systems.” *Journal of Materials in Civil Engineering*, DOI: 10.1061/(ASCE)MT.1943-5533.0001351, 04015078.

Leroueil, S.; Vaughan, P.R. (1990). “The general and congruent effects of structure in natural soils and weak rocks.” *Géotechnique*, 40(3), 467-488.

Lord, J.A.; Clayton, C.R.I.; Mortimore, R.N. (2002). “Engineering in chalk.” *CIRIA publication C574*, London, UK.

Mitchell, J.K. (1981). “Soil improvement – State-of-the-art report.” *Proceedings of the 10th international conference on soil mechanics and foundation engineering*, 4, 509–565. Stockholm, Sweden: International Society of Soil Mechanics and Foundation Engineering.

Mortimore, R.N., Stone, K. J.; Lawrence, J.; Duperret, A. (2004). “Chalk physical properties and cliff instability.” *Geological Society*, London, Engineering Geology Special Publications, 20(1), 75-88.

Portland Cement Association (1956). "Soil-Cement Construction Handbook." Chicago: *Portland Cement Association*.

Shihata, S.A.; Baghdadi, Z.A. (2001). "Long-term strength and durability of soil cement." *J. of Materials in Civil Engng.*, 13(3), 161–165.

Theivakularatnam, M.; Gnanendran, C.T. (2015). "Durability of lightly stabilized granular material subjected to freeze-thaw and wet-dry cycles." ASCE *IFCEE 2015*, 1410-1419.

Vaughan, P. R. (1997) "Engineering behavior of weak rocks: some answers and some questions – special lecture." *Int. Symposium on Geotechnical Engineering of Hard Soils – Soft Rocks*, Athens. Proceedings… Rotterdam: A. A. Balkema, 3, 1741-1765.

Zhang, Z.; Tao, M. (2008). "Durability of cement stabilized low plasticity soils." *Journal of Geotechnical and Geoenvironmental Engineering*, 134(2), 203–213.

NOTATION

ALM	*accumulated loss of mass*
C	*cement content (expressed in relation to mass of dry chalk putty)*
C_{iv}	*volumetric cement content (expressed in relation to the total specimen volume)*
CP	*chalk putty*
D_{50}	*mean particle diameter*
G_o	*initial shear modulus*
MLM	*middling loss of mass*
NC	*number of wetting/drying cycles*
q_u	*unconfined compressive strength*
R^2	*coefficient of determination*
η	*porosity*
η/C_{iv}	*porosity/cement index*
γ_d	*dry unit weight*
γ_s	unit weight of solids
w	*moisture content*

TABLES

Table 1. Physical properties of the chalk putty.

Liquid limit (%)	24
Plastic limit (%)	21
Plasticity index (%)	3
Specific gravity	2.8
Coarse sand (2.0mm < diameter < 4.75mm) (%)	9
Medium sand (0.425mm < diameter <2.0mm) (%)	22
Fine sand (0.075mm < diameter < 0.425mm) (%)	3
Silt (0.002 mm < diameter < 0.075mm) (%)	65
Clay (diameter < 0.002 mm) (%)	1
Mean particle diameter, D_{50} (mm)	0.035
Maximum dry unit weight for standard Proctor compaction effort (kN/m^3)	15.3
Optimum moisture content for standard Proctor compaction effort (%)	27
USCS class	ML (sandy silt)

FIGURE CAPTIONS

FIGURE 1. Variation of unconfined compressive strength (q_u) with adjusted porosity/cement index for chalk putty-Portland cement blends for 7 days of curing.

FIGURE 2: Initial shear modulus (G_0) versus adjusted porosity/cement index for 7 days of curing period.

FIGURE 3: Loss of mass versus number of wetting-drying cycles for chalk putty-Portland cement blends considering distinct dry unit weight (13.3, 14.3 and 15.3 kN/m^3) and cement content (3, 5 and 7%) specimens and 7 days as curing period.

FIGURE 4: Accumulated loss of mass versus number of wetting/drying cycles for chalk putty-Portland cement blends considering distinct dry unit weight (13.3, 14.3 and 15.3 kN/m^3) and cement content (3, 5 and 7%) specimens and 7 days as curing period.

FIGURE 5: Chalk putty-Portland cement blends accumulated loss of mass versus adjusted porosity/cement index after 3, 6, 9 and 12 wetting-drying cycles (during durability tests).

FIGURE 6: Chalk putty-Portland cement blends accumulated loss of mass versus adjusted porosity/cement index after wet-dry cycles during durability tests.

FIGURE 7: Initial shear modulus (G_0) versus number of the cycle after wetting-drying cycles during durability tests for chalk putty-Portland cement blends considering distinct dry unit weight (13.3, 14.3 and 15.3 kN/m^3) and cement content (3, 5 and 7%) specimens.

FIGURE 8: Relations between initial shear modulus (G_0) at specific number of the cycle (3, 6, 9 and 12) after wetting-drying cycles versus middling (average) loss of mass during durability tests for chalk putty-Portland cement blends considering distinct dry unit weight (13.3, 14.3 and 15.3 kN/m^3) and cement content (3, 5 and 7%) specimens.

Figure 1

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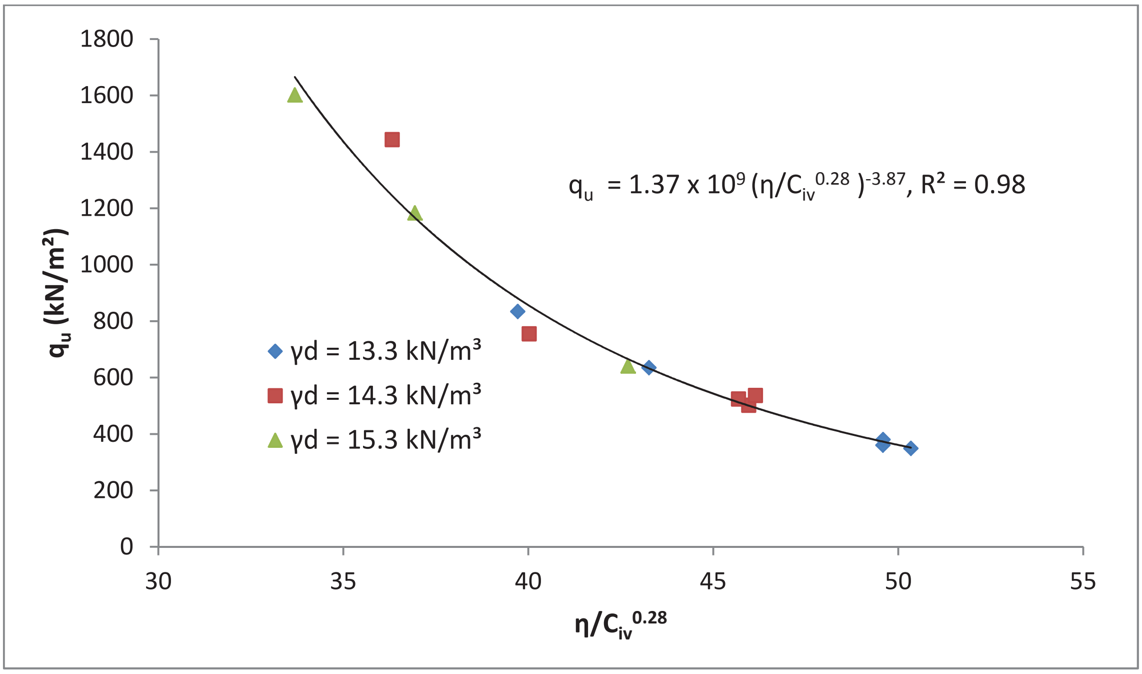

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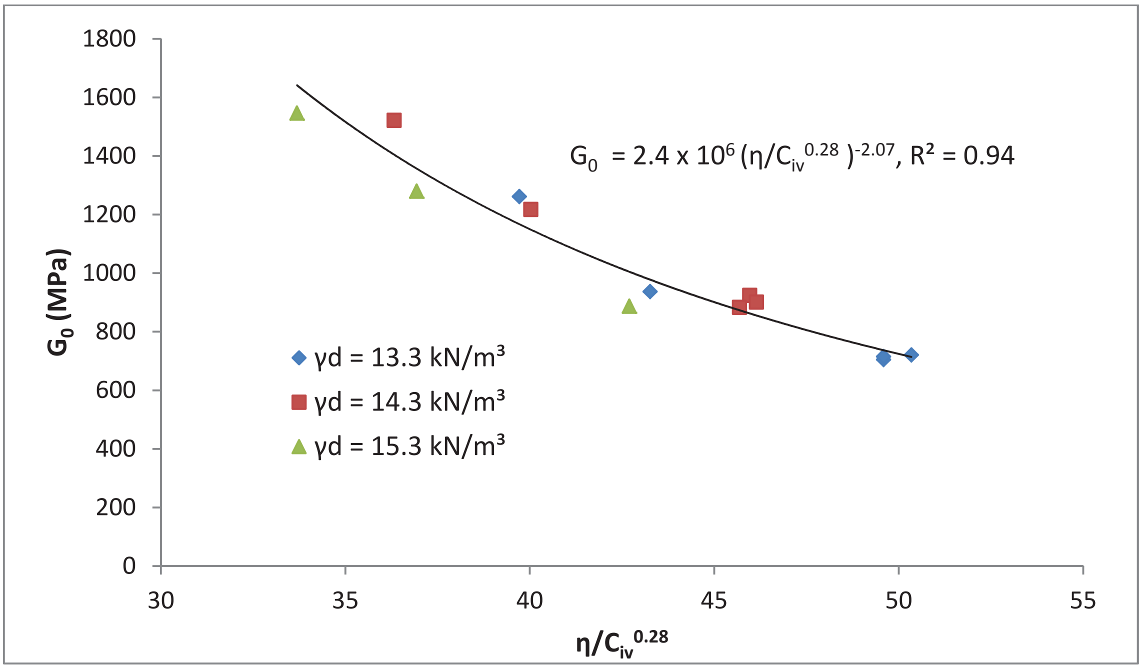

Figure 3

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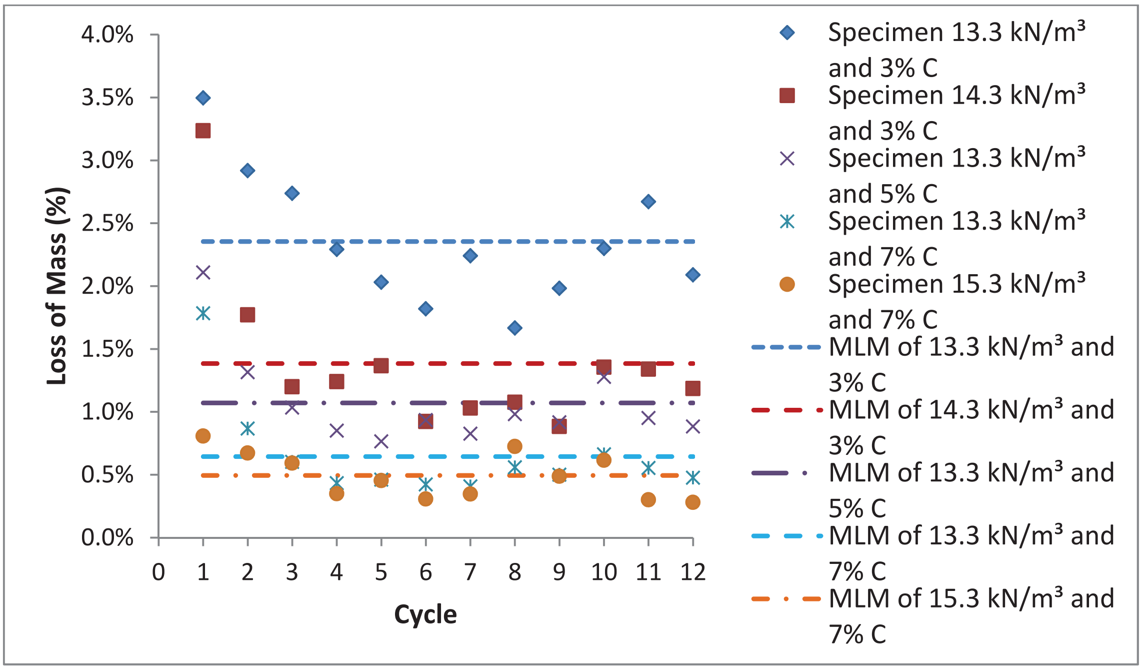

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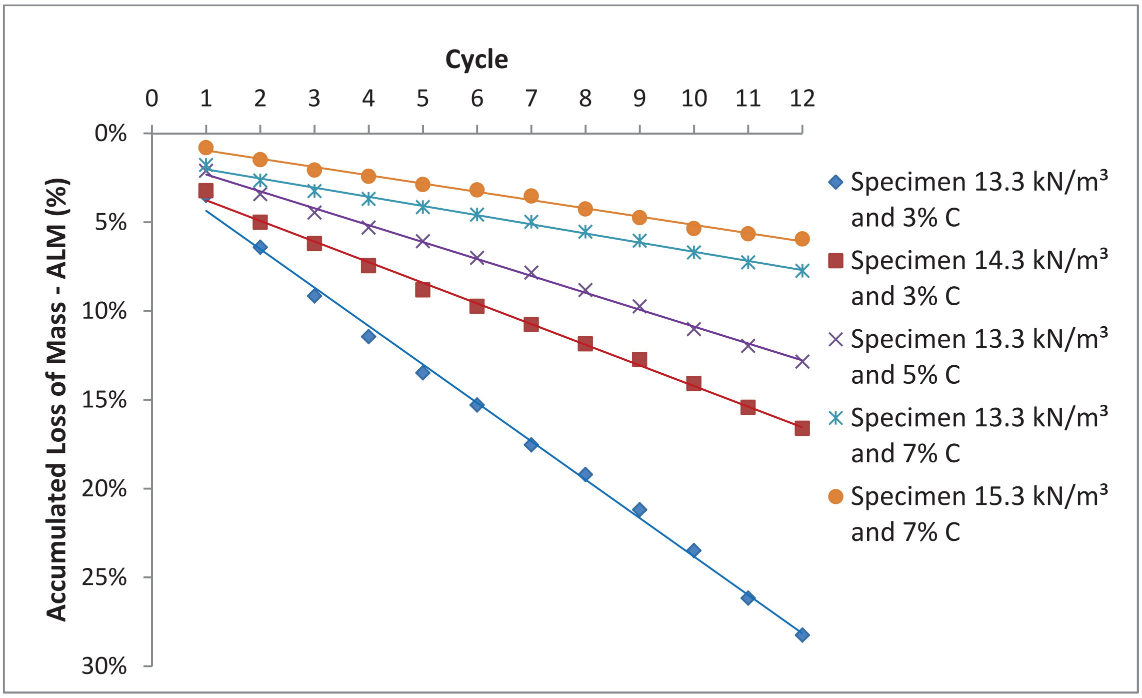

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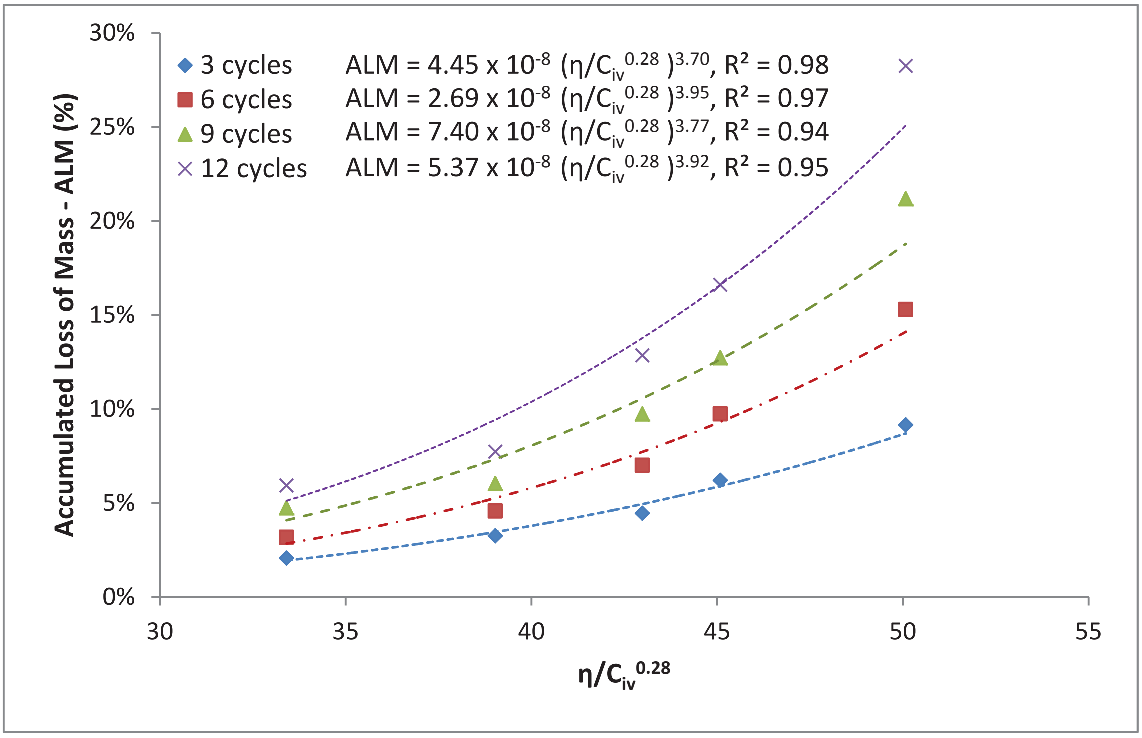


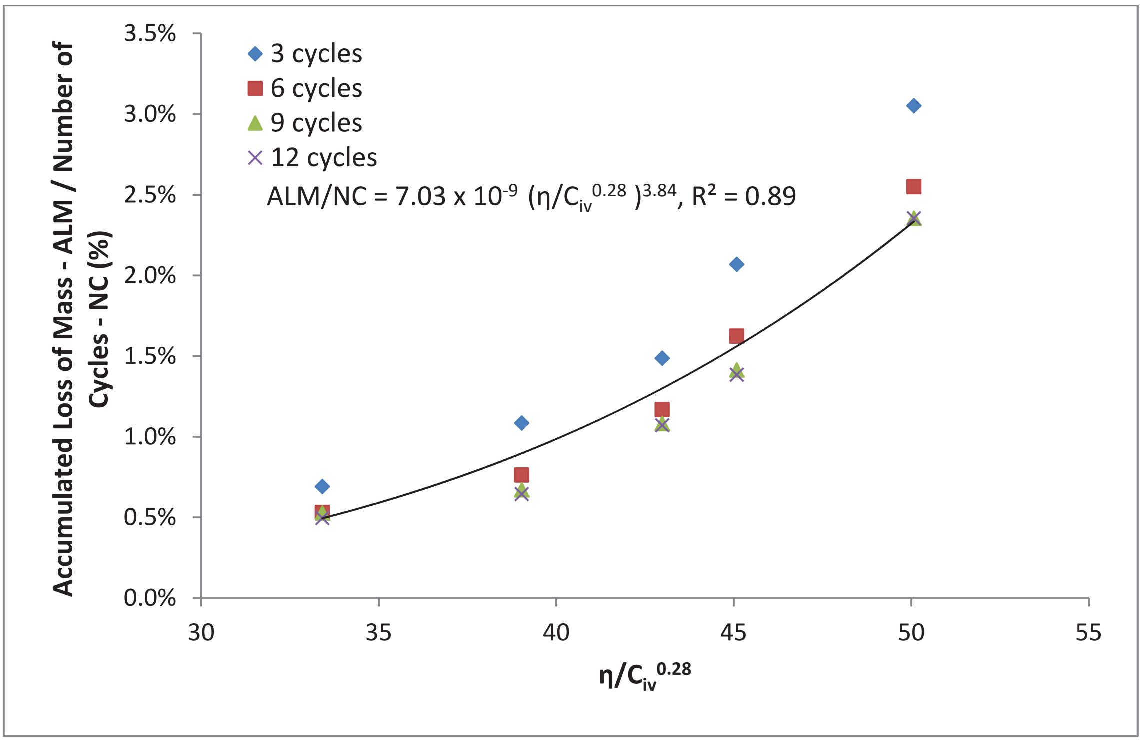
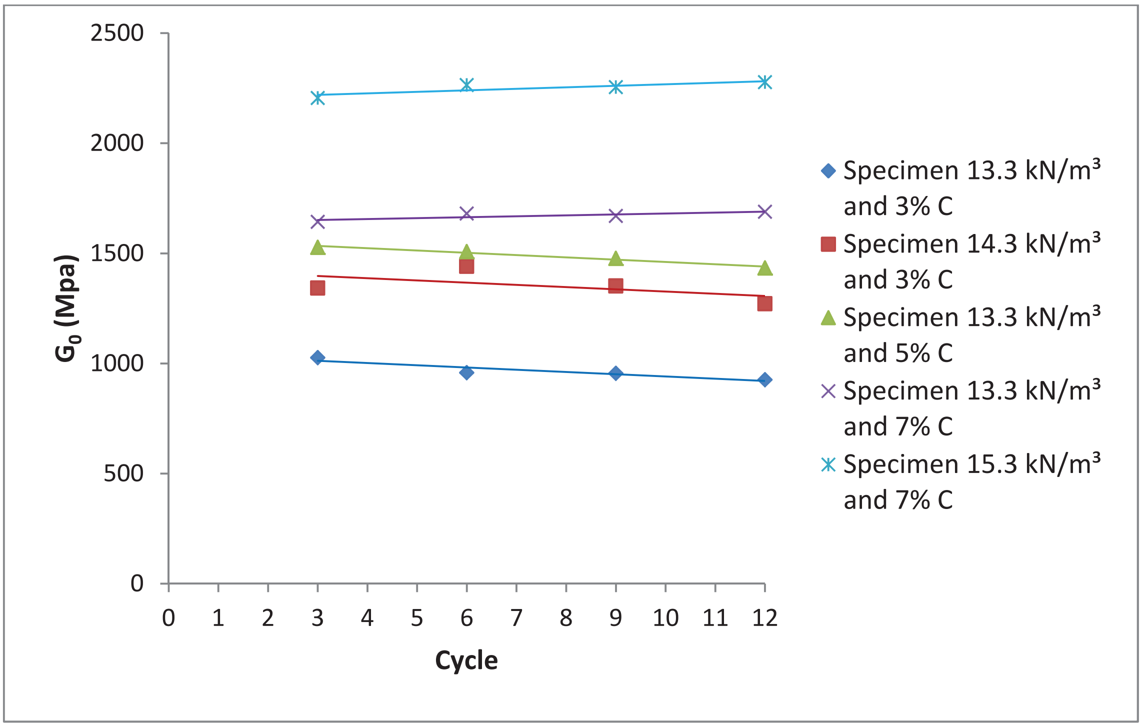
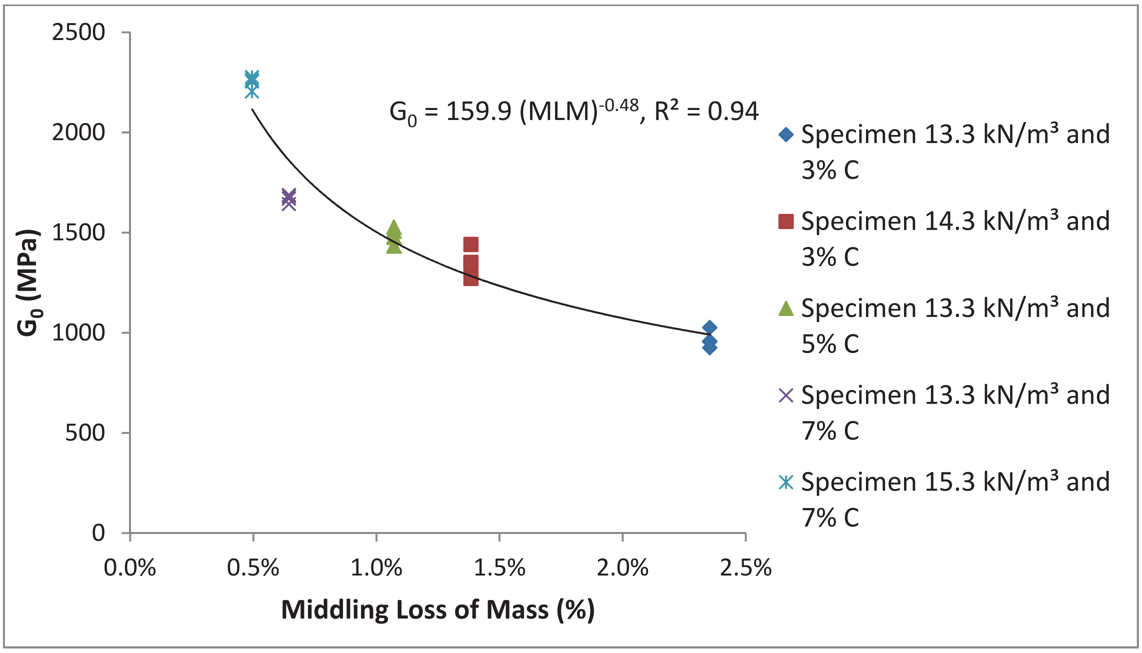

3 cycles
6 cycles
9 cycles
12 cycles
ALM/NC = 7.03 x 10-9 (η/Civ0.28)3.84, R² = 0.89
Accumulated Loss of Mass - ALM / Number of Cycles - NC (%)
3.5%
3.0%
2.5%
2.0%
1.5%
1.0%
0.5%
0.0%
30
35
40
45
50
55
η/Civ0.28

Figure 7


2500
2000
1500
1000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Cycle
G0 (Mpa)
Specimen 13.3 kN/m3 and 3% C
Specimen 14.3 kN/m3 and 3% C
Specimen 13.3 kN/m3 and 5% C
Specimen 13.3 kN/m3 and 7% C
Specimen 15.3 kN/m3 and 7% C


2500
2000
1500
1000
500
0
G0 (MPa)
G0 = 159.9 (MLM)-0.48, R² = 0.94
0.0%
0.5%
1.0%
1.5%
2.0%
2.5%
Middling Loss of Mass (%)
Specimen 13.3 kN/m³ and 3% C
Specimen 14.3 kN/m³ and 3% C
Specimen 13.3 kN/m³ and 5% C
Specimen 13.3 kN/m³ and 7% C
Specimen 15.3 kN/m³ and 7% C